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# Predictive Modelling of Axisymmetric Toroidal Configurations

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The Corsica 1-1/2D transport code [1], now a part of the LLNL/GA Caltrans transport code, has been used to simulate a variety of toroidal configurations both to predict expected behavior and to analyze existing experimental data. The principal purpose of this paper is to show Corsica's capability rather than in depth analyses of specific configurations. Much of this work emphasizes the influence of Ohm's law although we do include studies with temperature transport and driven current and heat sources. A special feature of this code is its ability to treat tokamaks in addition to both spheromaks and RFP's. The latter requires solving transport equations in poloidal flux coordinates rather than the standard toroidal flux coordinates.

**KSTAR CURRENT RAMP.** We have simulated two current ramps for the KSTAR tokamak. In one (I) we maintain a circular plasma till full bore and then increase the elongation to the initial flattop shape. In the other (II) we start shaping from the onset. The plasma becomes diverted about half way up the current ramp. The suggested parameters were provided by [2]. Our results show that, for both cases, $q_{axis}$ drops below one very early in the ramp indicating that the plasma is in a sawtooth phase. In general, the aim is to try to arrange for the onset of sawtooth activity to occur late in the ramp-up. The method of calculation is to fix the shape and plasma current as a function of time and then back out the required coil currents. For this calculation we have programmed in the suggested temperatures, densities and effective Z. The time evolution of the coil currents [1] is shown in Fig. 1, for a ramp time of 4 seconds. The swing in the current of coil 1 seems excessive. In this simulation we have used Spitzer conductivity to slow down the drop in $q_{axis}$. As a comparison, we have also used hyper-resistivity to emulate a

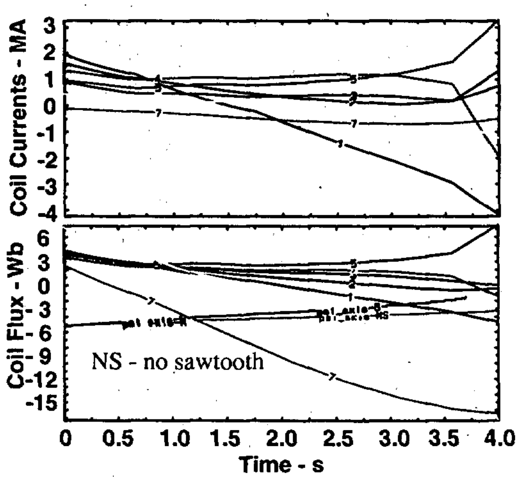


Figure 1. Coil currents and fluxes for KSTAR current ramp

sawtooth crash [3] and plot flux on axis; here we have used the correct neo-classical conductivity. This latter simulation fails at X-point formation because of the large sawtooth radius, about 75% of the minor radius. Similar results are seen for case (II), the ramp-up scenario suggested by KSTAR.

**ITER CONTROL.** In the above analyses the equilibrium was evolved with a fixed-boundary inverse solver (POLAR1). This was coupled to an R-Z free-boundary solver to back out the coil currents. We now describe results in which the full free-boundary equilibrium was used to simulate control of plasma position, shape and current. This study was done for the ITER EDA. Specifically, control is demonstrated for two classes of disturbances. In one we emulate ELMS by peeling off pressure at the edge for the old standard 21 MA ITER configuration. In the other, a minor disruption for a reverse shear equilibrium is simulated by rapidly dropping $\beta_{pol}$ and $l_i$ thereby raising $q_{min}$. During both of these disturbances helicity is conserved. In the former case the q-profile is conserved; in the latter case, the q-profile flattens in the reverse shear region subject to the magnitude of the drop. The changes were effected by instantaneously changing the equilibria. In both cases an ITER designed controller measuring 6 fiducial points ("gaps") was used. The time history of the "gaps" showing recovery after each disturbance is plotted in Fig. 2.

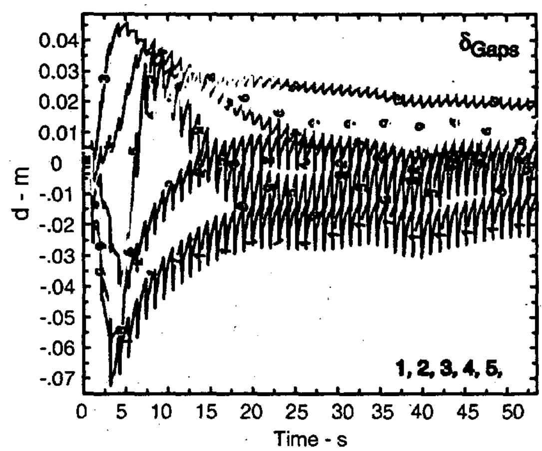

Figure 2. delta gap control during ITER ELM simulation; each spike is an ELM.

**MST TEARING.** The next simulations examine the effect of our "hyper-resistivity" (i.e., current-diffusion) [3] on both the MST RFP and the SSPX spheromak. For the RFP we determine unstable islands from a cylindrical Δ' analysis; then solve the Rutherford island equation to obtain the island width; and then feed this information to the hyper-resistive diffusion coefficient. The detailed scaling of this coefficient was motivated by Berk [4]. We then apply this model considering up to three unstable singular surfaces. The effect flattens the λ-profile ($J_{||}/B$) at the singular surface, thereby stabilizing the island; however, the model generates new structure at the edge of the island. This tends to destabilize adjacent islands. Clearly, this process would tend to generate a constant λ–profile, which is stable.

**SSPX HELICITY INJECTION.** The current profile in the Sustained Spheromak Physics Experiment, SSPX, has been reconstructed using Corsica's free-boundary equilibrium with current on the open field lines [5]. We model the evolution of the

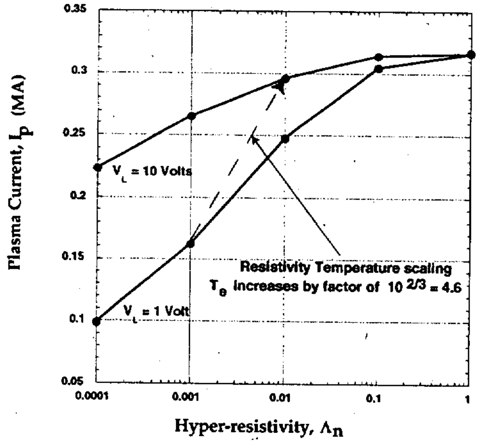


Fig. 3 Plasma current as a function of $V_L$ and $\Lambda_n$. To increase the current (see arrow) by raising the temperature with $\Lambda_n$=0 requires increasing the conductivity by 10.

current with fixed-boundary equilibria coupled with Ohm's law including hyper-resistivity with a constant coefficient, $\Lambda_n$. With this simple model we study the coupling of the current-carrying column along the geometric axis to the spheromak, to determine the sensitivity to both the loop voltage generated by instabilities in the column and the magnitude of $\Lambda_n$. For these initial calculations, partially summarized in Fig. 3, the experimentally measured electron temperature was used. It was found that: (1) at $\Lambda_n \sim 1$ the $\lambda$-profile was flat, and the plasma current was independent of the loop voltage; (2) at $\Lambda_n \ll 1$ the $\lambda$-profile is sensitive to loop voltage. Experimental lore has monotonic profiles; these profiles will be measured in SSPX in the near future experiment. Next, we plan to redo these calculations with the external currents and free-boundary equilibria to properly model the effect of the gun currents.

**DIIID/KSTAR MODELLING.** A major thrust of the DIII-D experimental program centers on the use of electron cyclotron heating (ECH) and current drive (ECCD) to improve and sustain advanced tokamak operating modes. Significant EC power will also be available on the KSTAR tokamak where similar EC-enhanced operations scenarios are currently being explored. The quiescent double barrier [6] has become a promising mode of operation on DIII-D where steady discharges have been formed with duration in excess of 3 seconds ($25\tau_E$). The formation of a core transport barrier and a quiescent H-mode [7] edge results in high normalized beta plasmas with electron temperature and density profiles favorable for absorption and high efficiency current drive. We simulate by using ECCD to control the q-profile shape while maintaining a high value for $q_{min}$ to reduce susceptibility to MHD activity as we scale to higher performance. We use the ray tracing module, Toray-GA, to calculate EC power deposition and current drive. Initial simulations with a single high power EC source maintained $q_{min}$ above 1.5 but the highly localized deposition profile resulted in

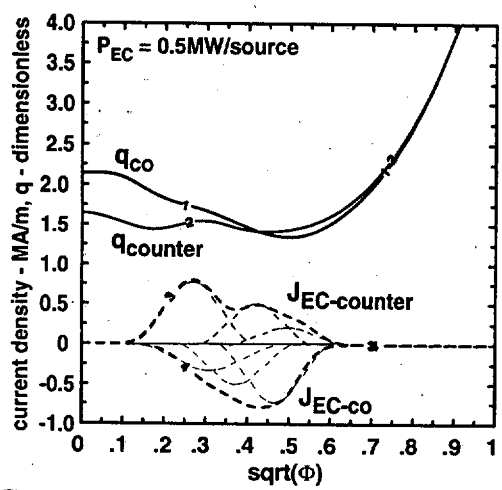


Figure 4. Co- and counter-ECCD profiles and the resulting q profiles at 3s for DIII-D shot 103818 conditions

a strong perturbation of the q-profiles. Present simulations with 3 separate sources independently controlled to broaden the deposition and current drive profile, Fig. 4, indicate that the core q profile can be controlled at a fixed value of $q_{95}$ with ECCD driven either along (co-ECCD) or opposite (counter-ECCD) the plasma current. The resulting equilibria are stable to ideal modes with a conducting wall (DCON [8]). We are now exploring extrapolations to steady-state operation (full non-inductively driven) that requires additional on-axis co-current drive to control $q_{axis}$ to compensate for the counter-injected neutral beams presently required for formation of QDB discharges. We are also exploring the use of ECH/ECCD in advanced tokamak scenarios for KSTAR negative central shear design similar to studies for DIII-D [9]. Our initial simulations explore the use of both NB and EC heating and current drive to maintain a desired q- profile in approaching steady-state conditions with full non-inductive current drive. Our current simulations control the q-profile late in time as the ohmic current dissipates (near zero loop voltage). We show in Fig. 5 one such simulation where a single EC source was modeled (using Toray-GA. The antenna launch angle was adjusted to control the resonance location in the poloidal plane (at a fixed toroidal angle) so as to maintain the current drive location as the ECH broadens the electron temperature profile. In these calculations, fixed thermal conductivities were used [2].

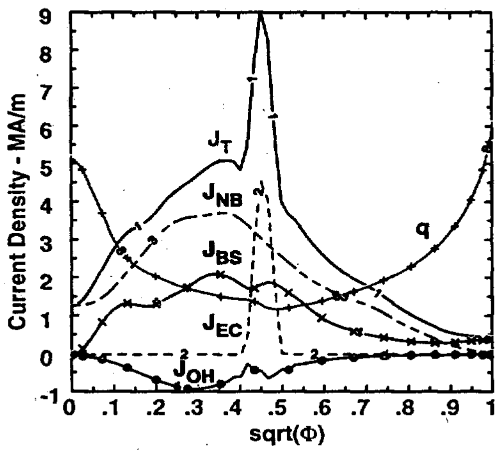

Figure 5. q and current profiles at 15s in KSTAR steady-state simulation


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